Black Hole Spins of Radio Sources

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ABSTRACT

A new approach to constraining or determining the spin of a massive black hole is proposed. A key parameter in the analysis is the dimensionless ratio, r, of the energy released to the mass of the hole. It is shown that the black hole spin j may be written as a function of the dimensionless ratio of the black hole spin energy to the black hole mass. When extraction of the black hole spin energy powers an outflow from the hole, the ratio r provides an indication of the black hole spin. The method is applied to a sample of 19 very powerful classical double radio galaxies with a range of size and redshift. The sources are found to have remarkably similar values of r and j, implying that the sources have very similar physical conditions at the time the outflow is generated. The weighted mean value of the spins is 0.12 ± 0.01. A sample of 29 central dominant galaxies is also studied; most of these sources have amorphous or FRI radio structure. The sources have a broad range of ratios r, and correspondingly broad range of black hole spins j with values from about 0.001 to 0.4, and a median value of about 0.03. The broad range probably results from the fact that each source is observed at a different stage in its lifetime. The intrinsic range of parameters could be as tight as it is for the powerful classical double radio galaxies.

Subject headings: black hole physics — galaxies: active — galaxies: nuclei

1. INTRODUCTION

Supermassive black holes are believed to power quasars and other types of AGN. The AGN activity manifests itself as radiation from the region around the black hole and as highly collimated outflows from the immediate vicinity of the black hole (e.g. Rees 1984). Two defining properties of astrophysical black holes that can be measured in principle are the black hole mass and spin. A significant amount of progress has been made toward measuring

the masses of supermassive black holes (e.g. Kormendy & Richstone 1995; Ferrarese & Ford 2005), though measuring the spin has been more challenging.

General theoretical studies of black hole spins indicate that accretion of gas is likely to produce rapidly spinning black holes (Volonteri et al. 2005), the merger of two nonspinning black holes of comparable mass is likely to produce a rapidly spinning black hole (Gammie, Shapiro, & McKinney 2004), and the capture of a smaller companion may cause the hole to spin down (Hughes & Blandford 2003). To date, there are only a few direct observations that allow black hole spins to be studied. Observations of Seyfert galaxies suggest rapidly rotating black holes in these systems (Wilms et al. 2001; Fabian et al. 2002). A large spin is indicated by observations of the Galactic Center black hole (Genzel et al. 2003; Ashenbach et al. 2004). And, X-ray observations of active galaxies suggest rapidly rotating black holes in these systems (Crummy et al. 2006).

Theoretical predictions for the spins of black holes for FRI and FRII radio sources (defined by Fanaroff & Riley 1974) have been made by Meier (1999) in the context of a rotating black hole model, and several predictions of this model are very similar to those obtained in the model of Blandford & Znajek (1977).

In this work, a new method of measuring the spin of a supermassive black hole is proposed. The method may be applied to sources with large-scale outflows that power radio sources, and, perhaps, other types of sources. A double radio source is powered by two oppositely directed highly collimated outflows from the vicinity of a supermassive black hole. The spin energy that is available to power the outflow can be written in terms of the black hole mass and spin. Thus, if the spin energy and black hole mass can be estimated or constrained, the black hole spin can be estimated or constrained.

The method to obtain a measure of the black hole spin is described in section 2. This method is independent of the specific model of energy extraction. The results obtained by applying the method are presented in section 3. A discussion follows in section 4. The results are obtained assuming a standard cosmological model with $H_o = 70$ km/s/Mpc, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and zero space curvature.

2. THE METHOD

The energy E_* that can be extracted from a black hole is related to the black hole spin $j \equiv (a/m)$ and mass M, as discussed, for example, by Blandford (1990), where a is defined in terms of the spin angular momentum S, the speed of light c and the black hole mass M, $a \equiv S/(Mc)$, and m is the gravitational radius of the black hole, $m = GM/c^2$. The spin

energy is $(M - M_i)c^2$, where M_i is the irreducible mass of the hole. Setting E_* equal to the spin energy and solving for the black hole spin, we find that

$$j = 2\ (2r - 5r^2 + 4r^3 - r^4)^{1/2} \tag{1}$$

where $r \equiv E_*/(c^2 M)$, or $j \approx (8r)^{1/2}$ for $r \ll 1$. Thus, for sources with outflows powered by the spin energy of a black hole, the black hole spin j can be measured when the total energy E_* of the outflow and the black hole mass M are known. Determinations of the black hole spin obtained using equation (1) do not depend upon the details of the energy extraction. The use of this equation assumes only that the ultimate source of the energy is the black hole spin, and that, during the short period of spin energy extraction, the black hole spin changes only because of the energy extraction.

The ratio r provides an important diagnostic of the black hole system. Studies of the ratio r provide insight into the physical state of the system at the time the outflow is generated irrespective of whether the outflow is powered by the spin energy of the hole.

3. RESULTS

3.1. Results Obtained with Powerful Classical Double Radio Galaxies

The spin energy of the black hole is thought to power the large-scale outflows from AGN (e.g. Blandford & Znajek 1977; Rees 1984; Blandford 1990; Wilson & Colbert 1995; Daly 1995; Meier 1999, 2002). The total energy E_* that will be channeled through a large-scale outflow can be determined for the most powerful classical double radio galaxies (e.g. Daly & Guerra 2002; Wan, Daly, & Guerra 2002; Daly et al. 2008; O'Dea et al. 2008). This empirically determined total energy E_* can then be combined with the black hole mass to obtain the ratio r and a measure of or bound on the spin parameter of sources using eq. (1). If only part of the spin energy is tapped, or if some of the tapped energy is dissipated or radiated away and does not reach the extremities of the radio source, the value of j obtained using eq. (1) will be a lower bound. If the outflows are powered by energy from some other source, such as an accretion disk, then the energy per unit black hole mass, r, could be used to probe the physics of the disk and, perhaps, place a limit on the black hole spin. For models in which the large scale outflow is powered by processes in the accretion disk, the black hole spin may be studied by combining the beam power of the outflow and mass of the black hole.

There are 19 powerful radio galaxies for which we have estimates of both the black hole mass M and the total energy E_*. All of these very powerful FRII radio sources have radio

powers at least a factor of ten above the classical FRI/FRII transition, and are referred to as FRIIb sources. The sources and their properties are listed in Table 1. The source redshifts range from 0.056 to 1.79, and the hot spot to hot spot source sizes range from about 100 kpc to over 600 kpc (O'Dea et al. 2008). The black hole mass for Cygnus A (3C 405) is obtained from Tadhunter et al. (2003); those for the next four sources are obtained from McLure et al. (2004), and those for the remaining 14 sources are obtained using equation (3) of McLure et al. (2006) where the values of M_{sph} were provided by McLure (McLure, private communication 2008). The total energies are obtained from Wan, Daly, & Guerra (2000), Guerra, Daly, & Wan (2000), and O'Dea et al. (2008) and converted to the cosmological model adopted here. The energy from the two sides of each source are combined to obtain the total outflow energy E_*, which is taken to be twice the weighted mean of the outflow energies from each side of the source. Deviations of the magnetic field strength of the extended radio source from the minimum energy value only enter E_* through the normalization of this quantity, as discussed in detail by O'Dea et al. (2008). The lobes of Cygnus A are used to normalize the sources, and an offset of 0.25 of magnetic field strength from the minimum energy value, appropriate for Cygnus A (Carilli et al. 1991; Wellman, Daly, & Wan 1997) has been adopted. Note that if there is no offset from minimum energy conditions in Cygnus A, the empirically determined values of E_* and r decreases by about a factor of 5 (O'Dea et al. 2008), so the values of j decrease by about $\sqrt{5}$ from those discussed below.

The dimensionless ratio of outflow energy to black hole mass, $r \equiv E_*/(c^2 M)$, is obtained for each source and substituted into eq. (1) to obtain the spin parameter j, and the values are listed in Table 1. The sources have very similar values of r and j, with no dependence of either parameter on source size or redshift. The weighted mean values of r and j for these 19 sources are $(1.6 \pm 0.3) \times 10^{-3}$ and 0.12 ± 0.01, respectively. Interestingly, within the measurement error, the values of r and j for each source are consistent with the mean value of the 19 sources. The values of j are shown as a histogram in Figure 1 and as a function of black hole mass in Figure 2. Figure 3 shows the total outflow energy as a function of black hole mass.

It would appear that the values of r and j for these FRIIb sources is constant, suggesting that the physical state of the system at the time the outflow is generated is very similar in each of the sources studied. This could indicate that the outflow is triggered when a particular threshold, given by $r \approx 10^{-3}$, is reached. A model that includes a threshold of this type is discussed by Meier (1999). A threshold for the onset of the outflow is also indicated by a comparison of individual source properties with the properties of the full population of sources (e.g. Daly & Guerra 2002; Daly et al. 2008).

3.2. Results Obtained with Central Dominant Galaxies

There are now many examples of galaxy clusters in which the intracluster medium (ICM) has been displaced as the result of powerful outflows from AGN (e.g. McNamara & Nulsen 2007; Rafferty et al. 2006). The displacement of the ICM provides a measure of the total energy that has been pumped into the ICM by the large-scale outflow from the AGN associated with the central dominant galaxy (CDG). If the highly collimated outflow is powered by the spin energy of the AGN, then the energy of the outflow and the mass of the black hole can be combined to solve for the spin j of the black hole. Of the 33 galaxy clusters studied by Rafferty et al. (2006), 29 have estimates of both the mass of the black hole associated with the large-scale outflow and the total energy input to the ICM by the AGN. One source, A1068, does not have an estimate of the total energy input to the ICM by the AGN, and three sources, RBS 797, MACS J1423.8+2404, and 3C401, do not have estimates of the black hole mass. The remaining 29 sources are considered here. Almost all of these sources have FRI radio source structure or have amorphous radio structure, with a few exceptions such as Cygnus A (Birzan et al. 2008).

Equation (1) was used to estimate the spin of each of the 29 sources for which there is a measure of both the energy E_* and the black hole mass M. The energy $E_* = 4PV$ and black hole mass for each source are obtained from Rafferty et al. (2006), where the values of M_{BH,L_K} are used since they are obtained in a manner that is very similar to the black hole mass determinations described in section 3.1. The values of M_{BH,L_K} listed in Table 3 of Rafferty et al. (2006) had been modified by those authors by a factor of 0.35, and this adjustment has been removed. This brings the mass estimates for Cygnus A (3C 405) and M84 into good agreement with the independent determinations by Tadhunter et al. (2003) and Maciejewski & Binney (2001), respectively. For simplicity, the average value of asymmetric error bars was used.

The values obtained for the ratio r and spin j of each source are listed in Table 2. The median value of j is 0.026, the average value of $\log j$ is -1.53 ± 0.03, and the values of j range from about 0.001 to 0.4. A histogram of the values of $\log(j)$ is shown in Figure 1, and j is shown as a function of black hole mass in Figure 2. Figure 3 shows the total outflow energy as a function of black hole mass. Clearly, there is a much broader range of E_*, r, and j for the CDGs relative to those of powerful classical double radio galaxies. Most of the values of $\log(j)$ lie in the range from 10^{-1} to 10^{-2}. The values of the energy extracted for the 29 CDGs studied include the energy extracted up to the time of observation, and each source is being observed at a different stage in its lifetime. In addition, relativistic plasma left from a prior outflow event could cause the outflow energy from the current outflow event to be overestimated. These effects can cause the observed distributions of r and j to be quite

broad.

4. DISCUSSION

The range of values of r and j for the FRIIb radio galaxies studied is remarkably small, while the range of values of r and j for outflows associated with CDGs is quite broad. There are two key distinctions between these samples that may partially explain these differences. Firstly, the outflow energy measured for a FRIIb source is an estimate of the total outflow energy that will be produced over the entire lifetime of the outflow, whereas the outflow energy measured for the CDGs is an estimate of the outflow energy produced by the source up to the time of the observation. Catching each CDG outflow at a different phase in the course of its lifetime will cause the distribution of outflow energies for CDGs to be broad; this is not a factor for the FRIIb sources. In addition, a prior outflow event from a CDG could cause the outflow energy of a given event to be overestimated. Secondly, the FRIIb radio galaxies are selected from the flux limited 3CRR catalogue (Laing, Riley, & Longair 1983), so only the most powerful sources are detected at each redshift. Interestingly, the total outflow energy E_* measured for powerful 3CRR radio galaxies increases as $(1+z)^{1.8\pm0.2}$ (O'Dea et al. 2008), while the black hole mass rises as $(1+z)^{2.07\pm0.76}$ (McLure et al. 2006), so the ratio r is independent of redshift. The fact that lower mass and lower energy black holes are not observed at high redshift is due to the flux limit of the survey. The fact that the high mass and high energy sources FRIIb sources are not seen at low redshift may suggest that the higher mass sources are more active at high redshift, or that changes in the environment cause the radio power of the sources to fall below the flux limit of the survey, that is, the sources may be lower power FRII sources or FRI sources, though they could still have large outflow energies (e.g. Hardee et al. 1992; O'Donoghue, Eilek, & Owen 1993; Bicknell 1995). A selection bias also seems to be present in the CDG sample; the 6 sources with outflow energies less than $10^4 c^2 M_{\odot}$ are all at very low redshift, and the outflow energy, black hole mass, and black hole spin all tend to increase with redshift.

Very powerful 3CRR radio galaxies are likely to evolve into the CDGs (Lilly & Longair 1984; Best et al. 1998; McLure et al. 2004). Thus, the two samples studied are representative of the early and late phases of evolution of these systems. The systems have black holes with similar mass. Clearly, the FRIIb sources have a very small range of outflow energy per unit black hole mass, r. It would appear that there is a larger range of values for this parameter for CDGs, but, given the factors affecting the measurements of outflow energy from black holes of CDGs, it is possible that these sources have a similarly small intrinsic range of r and j.

The results obtained here are consistent with the idea that the different radio structures of FRI and FRII sources are due to differences in their gaseous environments (e.g. Burns et al. 1994; Bicknell 1995), and suggests that the gaseous environments of these sources has evolved significantly. The evolution of the gaseous environment could be due in part to the large-scale outflows (e.g. Silk & Rees 1998; Eilek & Owen 2002).

It is remarkable that so few sources have values of j close to the theoretical limit of unity; that is, almost all sources have values of r much less than the theoretical limit of 0.29. All of the FRIIb sources have $r \sim 10^{-3}$. This suggests that each system is in a similar physical state at the time the outflow is generated, and may indicate that the outflow is triggered when a particular threshold is reached. If the sources have intrinsic values of j that start out close to one, each outflow event is tapping a very small fraction of the available spin energy, and each source may have multiple outflow events.

The spin values obtained here could be compared with independent measures of the black hole spin. This may provide a diagnostic of whether it is the black hole spin or the accretion disk that is powering large-scale outflows from these sources. In addition, the method of using outflow energies and black hole masses to estimate black hole spins presented here may be applicable to other systems.

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Table 1. FRIIb Black Hole Properties

Source	z	E_*/c^2 ($10^6 M_\odot$)	M ($10^8 M_\odot$)	$r \equiv E_*/(c^2 M)$ (10^{-3})	j
3C 405	0.056	3.2 ± 0.6	25 ± 7	1.3 ± 0.4	0.10 ± 0.02
3C 244.1	0.43	1.8 ± 0.3	9.5 ± 6.6	1.9 ± 1.4	0.12 ± 0.04
3C 172	0.519	2.8 ± 0.6	7.8 ± 5.4	3.6 ± 2.6	0.17 ± 0.06
3C 330	0.549	4.3 ± 0.9	13 ± 9	3.3 ± 2.4	0.16 ± 0.06
3C 427.1	0.572	2.6 ± 0.6	15 ± 10	1.8 ± 1.3	0.12 ± 0.04
3C 337	0.63	2.3 ± 0.5	9.1 ± 6.2	2.5 ± 1.8	0.14 ± 0.05
3C34	0.69	3.8 ± 0.7	16 ± 11	2.4 ± 1.7	0.14 ± 0.05
3C441	0.707	4.1 ± 0.7	18 ± 12	2.3 ± 1.7	0.14 ± 0.05
3C 55	0.735	6.2 ± 1.3	14 ± 10	4.3 ± 3.2	0.18 ± 0.07
3C 247	0.75	3.0 ± 0.6	26 ± 18	1.2 ± 0.9	0.10 ± 0.04
3C 289	0.9674	4.3 ± 0.9	27 ± 21	1.6 ± 1.3	0.11 ± 0.05
3C 280	0.996	3.6 ± 0.7	27 ± 21	1.3 ± 1.1	0.10 ± 0.04
3C 356	1.079	7.6 ± 1.8	28 ± 22	2.7 ± 2.3	0.15 ± 0.06
3C 267	1.142	6.5 ± 1.3	24 ± 20	2.6 ± 2.2	0.15 ± 0.06
3C 324	1.206	5.8 ± 1.4	37 ± 30	1.6 ± 1.4	0.11 ± 0.05
3C 437	1.48	13 ± 3	24 ± 22	5.5 ± 5.1	0.21 ± 0.10
3C 68.2	1.575	6.8 ± 1.5	35 ± 32	2.0 ± 1.9	0.13 ± 0.06
3C 322	1.681	10.6 ± 2.2	32 ± 30	3.3 ± 3.2	0.16 ± 0.08
3C 239	1.79	10.2 ± 3	37 ± 36	2.8 ± 2.8	0.15 ± 0.07

Table 2. CDG Black Hole Properties

Source	z	E_*/c^2 $(10^6 M_\odot)$	M $(10^8 M_\odot)$	$r \equiv E_*/(c^2 M)$ (10^{-3})	j
MS 0735.6+7421	0.216	36 ± 26	20 ± 11	18 ± 16	0.37 ± 0.16
Zw 2701	0.214	7.8 ± 8.1	17 ± 9	4.5 ± 5.2	0.19 ± 0.11
Hydra A	0.055	1.4 ± 0.7	11 ± 4	1.2 ± 0.7	0.10 ± 0.03
Zw 3146	0.291	8.4 ± 6.3	74 ± 53	1.1 ± 1.2	0.10 ± 0.05
MKW 3S	0.045	0.84 ± 0.48	8.6 ± 2.9	0.99 ± 0.65	0.089 ± 0.029
Cygnus A	0.056	1.9 ± 0.9	29 ± 14	0.65 ± 0.46	0.072 ± 0.025
PKS 0745-191	0.103	1.5 ± 0.7	31 ± 16	0.49 ± 0.34	0.062 ± 0.022
Hercules A	0.154	0.69 ± 0.54	20 ± 11	0.34 ± 0.34	0.052 ± 0.026
Sersic 159/03	0.058	0.56 ± 0.38	17 ± 9	0.32 ± 0.27	0.051 ± 0.021
A133	0.060	0.53 ± 0.13	20 ± 10	0.27 ± 0.15	0.046 ± 0.013
Perseus	0.018	0.42 ± 0.28	17 ± 7	0.25 ± 0.19	0.044 ± 0.017
A1835	0.253	1.0 ± 0.7	54 ± 36	0.19 ± 0.19	0.039 ± 0.019
4C 55.16	0.242	0.27 ± 0.18	14 ± 7	0.19 ± 0.16	0.039 ± 0.016
A2597	0.085	0.080 ± 0.068	8.6 ± 2.9	0.093 ± 0.085	0.027 ± 0.012
A2199	0.030	0.17 ± 0.09	20 ± 9	0.083 ± 0.057	0.026 ± 0.009
3C 388	0.092	0.12 ± 0.11	17 ± 7	0.067 ± 0.068	0.023 ± 0.012
A1795	0.063	0.10 ± 0.09	23 ± 11	0.046 ± 0.046	0.019 ± 0.010
A4059	0.048	0.067 ± 0.038	29 ± 14	0.023 ± 0.018	0.014 ± 0.005
A2052	0.035	0.038 ± 0.033	17 ± 7	0.022 ± 0.022	0.013 ± 0.006
A2029	0.077	0.11 ± 0.03	60 ± 36	0.018 ± 0.012	0.012 ± 0.004
2A 0335+096	0.035	0.024 ± 0.014	14 ± 7	0.017 ± 0.013	0.012 ± 0.005
A478	0.081	0.033 ± 0.017	26 ± 14	0.013 ± 0.010	0.010 ± 0.004
A85	0.055	0.027 ± 0.018	29 ± 14	0.0093 ± 0.0078	0.0086 ± 0.0036
PKS 1404-267	0.022	0.0027 ± 0.0022	5.7 ± 2.9	0.0047 ± 0.0045	0.0061 ± 0.0030
A262	0.016	0.0029 ± 0.0014	8.6 ± 2.9	0.0034 ± 0.0020	0.0052 ± 0.0016
HCG 62	0.014	0.0010 ± 0.0011	5.7 ± 2.9	0.0018 ± 0.0022	0.0038 ± 0.0023
Centaurus	0.011	0.0013 ± 0.0007	8.6 ± 2.9	0.0016 ± 0.0010	0.0035 ± 0.0011
M87	0.0042	0.00044 ± 0.00019	8.6 ± 2.9	0.00052 ± 0.00028	0.0020 ± 0.0006
M84	0.0035	0.000067 ± 0.000078	3.4 ± 0.9	0.00019 ± 0.00023	0.0012 ± 0.0007

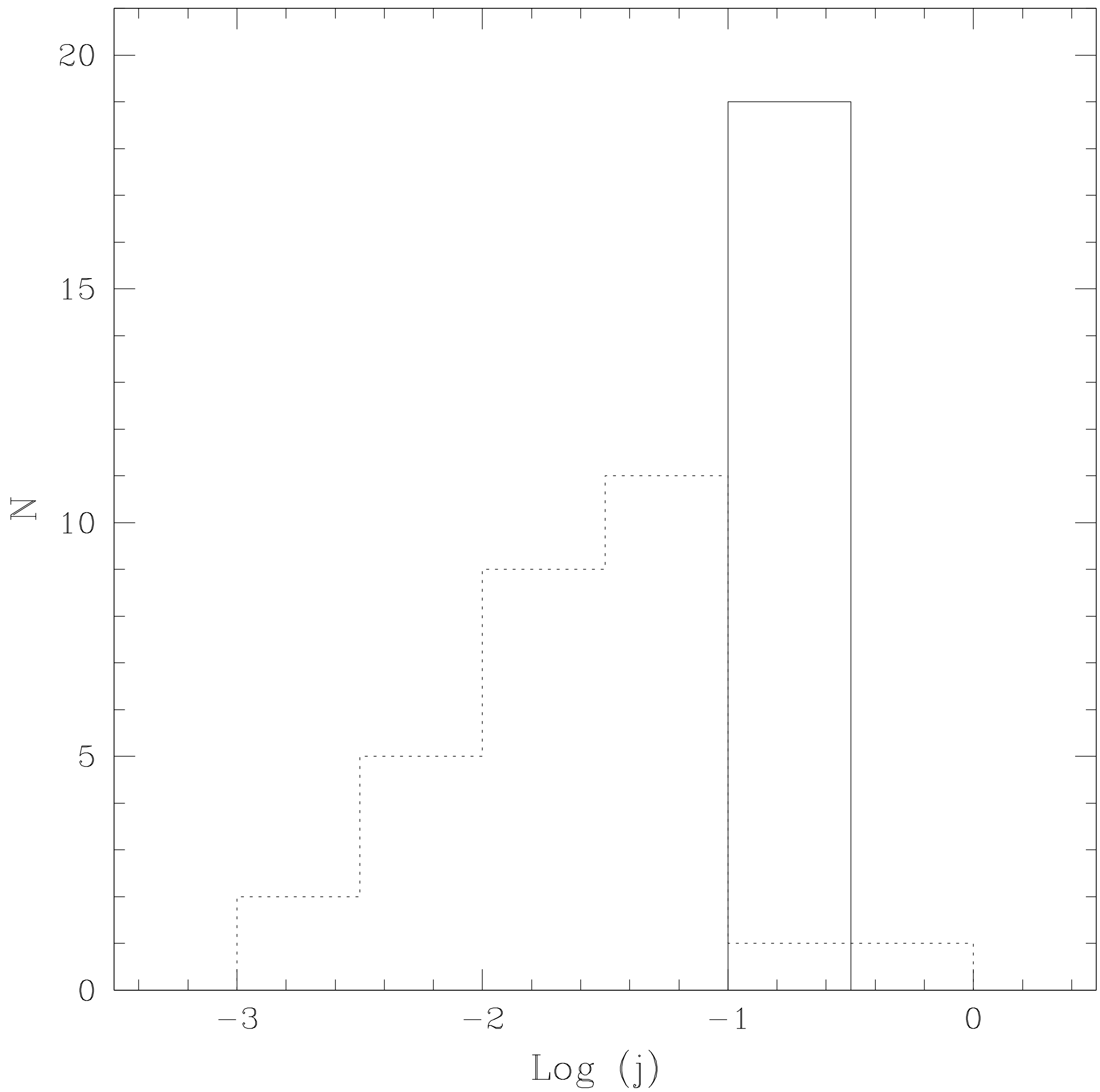

Fig. 1.— Histogram of spin values. The dotted line indicated the histogram for the sample of 29 central dominant galaxies, while the solid line indicates that for the sample of 19 powerful classical double radio galaxies.

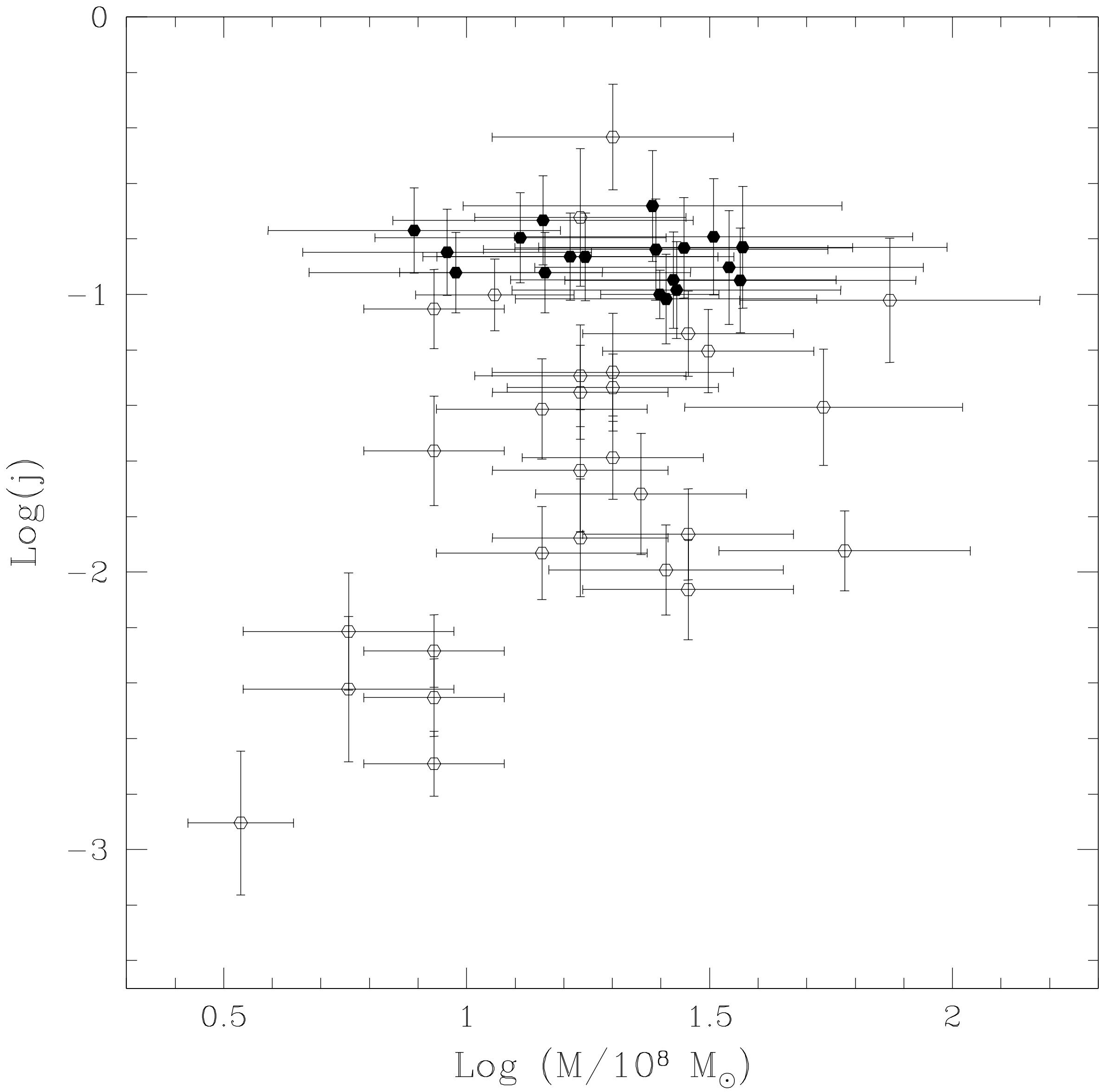

Fig. 2.— Distribution of black hole spin as a function of black hole mass. The 19 sources associated with very powerful classical double radio galaxies are indicated by solid circles, and the 29 sources associated with CDGs are indicated by open circles. One source, Cygnus A (3C 405) is included in both samples.

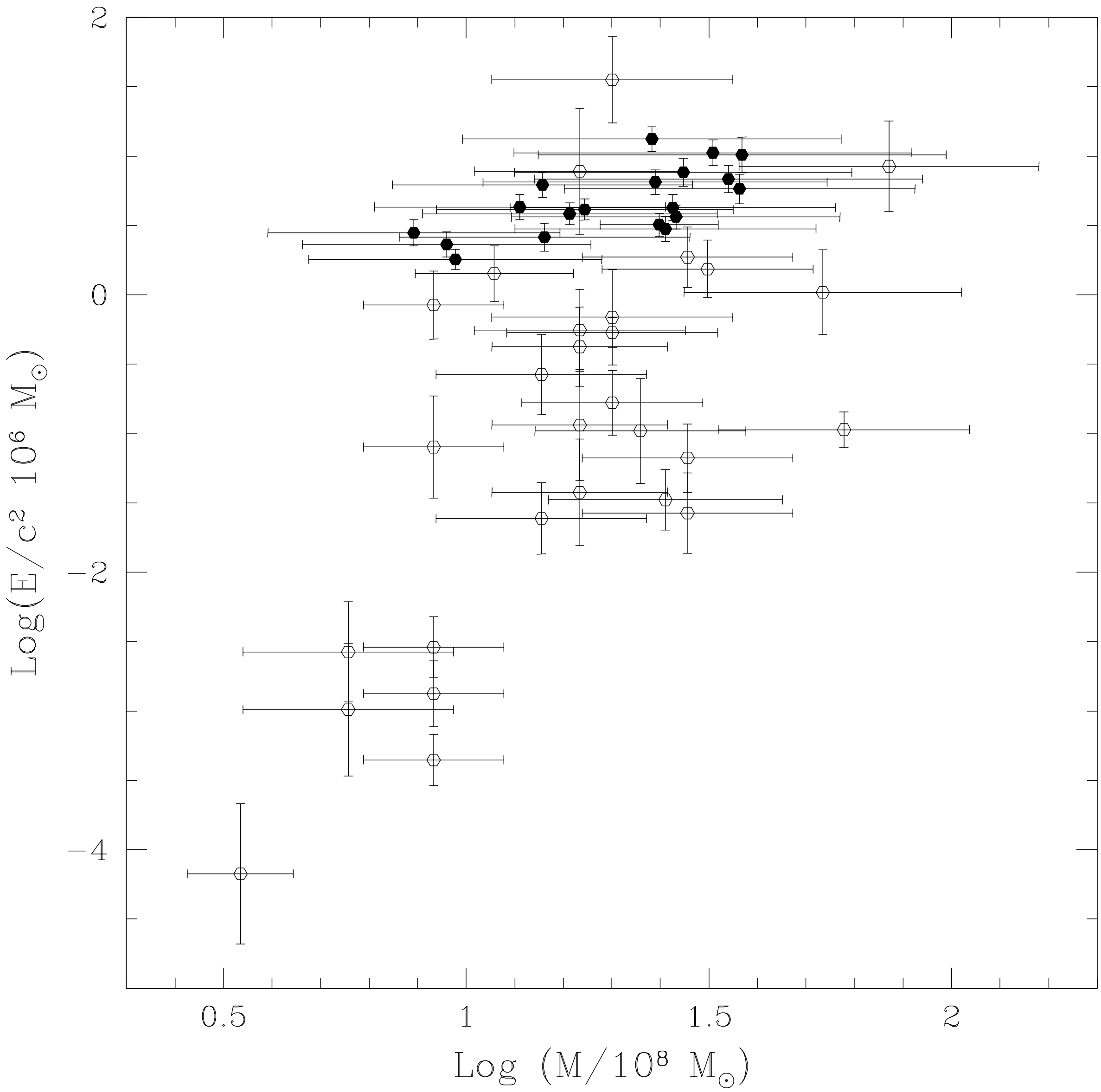

Fig. 3.— Distribution of outflow energy as a function of black hole mass; the symbols are as in Fig. 2.